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Groundwater–surface water interactions in a North German lowland floodplain – Implications for the river discharge dynamics and riparian water balance

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Summary Water balance and groundwater dynamics of a floodplain catchment in the Northeast German lowlands are investigated with consideration of the variable interactions between the riparian groundwater and surface water. Based on experimental and numerical investigations, evidence is given for temporally and spatially variable exchange fluxes between groundwater and surface water, which have significant impact on the riparian water balance and groundwater recharge.

A coupled soil water balance–groundwater model is used for the quantification of exchange fluxes across the groundwater–surface water interface and the groundwater recharge for nested catchments in a typical floodplain representative for the Central European lowland catchments.

Simulation results indicate substantial exchange fluxes between groundwater and the river, which are subjected to intensive spatial and temporal variability. The intensities and also the directions of exchange fluxes in particular stream reaches are characterised by transient alterations. Groundwater–surface water interactions are found to control the groundwater recharge dynamics in the floodplain and outweigh the influence of vertical percolation and root water uptake. Although groundwater contributions from this river stretch represent only 1% of the annual total discharge within the river its impact is much higher during low flow conditions in summer when ca. 30% of the river runoff which is generated in the catchment is originated by groundwater discharge from the riparian zone along this river stretch.

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The results of this study show that groundwater—surface water interactions within the investigated riparian floodplain are far too complex for the traditional classification concept distinguishing between loosing and gaining sections. The temporally variable impact of groundwater—surface water interactions furthermore highlights the necessity to consider seasonal effects when assessing the significance floodplain processes and functions.

Introduction

Lowland rivers, embedded in extensive alluvial floodplains, cover substantial parts of the glacially formed landscape of North and Central-west Europe. They are usually characterised by low flow velocities, especially during summer and a riparian zone representing a buffer between the aquatic and terrestrial environment. Riparian zones often consist of fluvially derived sediments and are characterised by widely distributed riparian wetlands (Woessner, 2000; Gregory et al., 1991; Steiger et al., 2005).

Floodplains provide a broad variety of hydrological and ecological functions such as regulation of runoff generation (Woessner, 2000; Butturini et al., 2002), retention during hydrological extremes (Sophocleous, 2002; Krause and Bronstert, 2004, 2007) and biogeochemical transformations including natural attenuation of nutrients and pollutants (Hill, 1996; Triska et al., 1989, 1993; Lowrance et al., 1984; Brunke and Gonser, 1997; Duff and Triska, 1990). Due to their hydro-geomorphological characteristics they represent an important ecological niche and may form important fall back biotopes for endangered species (Steiger et al., 2005; Standford, 1998).

During the last century floodplains of northern hemisphere have been subjected to intensive changes in landuse and management (Krause et al., 2007; Mohrlock, 2003; Sophocleous, 2002; Brunke and Gonser, 1997; Hancock, 2002). Hence, their water balance, natural regulatory functions for aquatic and groundwater chemistry and their ecological value are often altered (Sophocleous, 2002; Hancock et al., 2005; Hayashi and Rosenberry, 2002).

Article 4 of the European Water Framework Directive (WFD; 2000/60/EU) demands that all water bodies achieve a set of environmental objectives. These objectives target the good chemical and ecological status of surface water bodies as well as a good chemical and quantitative status of groundwater bodies.

In light of the demands of the European Water Framework Directive, the regulatory functions of lowland floodplains for water balance and chemistry, especially during dry periods, become of increasing interest for research and management (Woessner, 2000; Standford, 1998; Krause et al., 2007).

Many of the eco-hydrological functions of floodplains are strongly related to the interactions between the floodplains shallow groundwater and the surface water of the usually well connected lowland rivers (Butturini et al., 2002; Hancock et al., 2005; Hayashi and Rosenberry, 2002).

The intensity of these interactions and the resulting exchange fluxes between groundwater and surface water depend on pressure head gradients between the floodplain groundwater and the river as well as on the connectivity between both water bodies (Sophocleous, 2002; Bencala, 1993; Stanford and Ward, 1993).

The connectivity is controlled by the permeability of the stream bed and the aquifer, by the channel position in regard to the groundwater as well as by the geometry and size of the contact area (Winter et al., 1998; Wroblicky et al., 1998; Woessner, 2000; Harvey and Bencala, 1993).

Under low and intermediate flow conditions the contact area is usually determined by the channel geometry (Woessner, 2000; Sophocleous, 2002). However, during flood situations the river water level may rise above the river bank, and the geometry of the floodplain controls the exchange interface.

The interactions between groundwater and surface water and the resulting exchange fluxes are often characterised by a high temporal and spatial variability. Commonly the type of interaction is described by the direction of the exchange fluxes distinguishing between influent (flowing in) fluxes and effluent (flowing out) fluxes. Based on these fluxes the investigated streams/stream reaches are described as loosing, gaining and through flow or parallel flow (Sophocleous, 2002; Winter et al., 1998; Woessner, 2000). The reference point for the description of these fluxes depends on the perspective of the subject and the author (Schmidt et al., 2006; Packman and Bencala, 2000), which is not unique and thus, the use of these terms can be inconsistent. In this study influent fluxes describe the infiltration of surface water into the groundwater of the floodplain, effluent fluxes describe the exfiltration of groundwater into the river.

In this study the seasonal variability of groundwater—surface water exchange fluxes and its spatially and temporally variable impact on the water balance and river discharge are investigated for subcatchments in the floodplain of the Havel River in Northeast Germany which is an example for many floodplains in Northwest Europe.

Within the present study we aim to give experimental and numerical evidence that:

- Influent and effluent conditions may occur simultaneously in different river sections.
- The spatial pattern of groundwater—surface water interactions along the river is not constant but exhibits a seasonal dynamic that is crucial for the floodplain water balance, river discharge and chemistry.
- Groundwater—surface water exchange fluxes can have a temporally variable impact on the hydrological processes within the floodplain and discharge conditions within the river which subsequently affect the ecological processes and the status of the water body.

The investigations are based on analyses of discharge data from a nested observation network. Furthermore, a model which has been shown to portray the riparian hydrological processes appropriately (Krause and Bronstert, 2004,

2007) is employed to perform long-term simulations of the riparian exchange fluxes and water balance.

Materials and methods

Study area

Wide parts of the glacially formed North-eastern German lowlands are characterised by a low topographic energy and extensive floodplains, which are widely covered by groundwater dependent wetlands. The Havel river basin, represents a typical example of the floodplain dominated lowland landscapes of the North-eastern German Lowlands. The Havel river has a total length of 325 km and its catchment covers an area of ca. 24,000 km^2 before the Havel River discharges into the Elbe River.

The water levels within the Lower and Central Havel river are regulated by a network of weirs in order to store water during the rather wet period from autumn to spring. The major intention for this is to ensure a minimum discharge and water level in summer, which may otherwise reach a critical condition for both ecological processes and the accessibility for inland cargo vessels.

The experimental and model based investigations presented in this study took place in several subcatchments at the Lower and Central Havel River (roughly between the city of Potsdam and ca. 20 km upstream of the confluence with the Elbe river) (Fig. 1). Catchment areas vary from ca. 1 km^2 to ca. 1000 km^2 and are presented in Table 1.

The most characteristic landscape element is the extensive floodplain in the central part of the catchment. The average altitude of the floodplain is 25–28 m asl. The Pleistocene moraines, which surround the floodplain, reach heights of 120 m asl.

The floodplain of the Lower Havel River represents one of the largest inland wetlands of Central Europe and is of high ecological value, in particular for bird populations. A large area of the floodplain is protected by German and European nature conservation law.

The average annual precipitation is 540 mm a^{-1}. The organic rich sands and loamy sands within the floodplain show lower hydraulic conductivities (2.3×10^{-7}–2.1×10^{-6} m s^{-1}) than the sandy soils of the moraines (1.2–4.2×10^{-4} m s^{-1}). However, the infiltration capacity usually exceeds even the highest rainfall intensities of the area and thus, prevents infiltration excess overland flow (Krause and Bronstert, 2004, 2007).

The catchment has been characterised for centuries by periodic inundation of large parts of the floodplain (mainly due to backwater and retarded discharge into the Elbe River). To enable and maximise the agricultural use of the floodplain, the landscape has been equipped with a dense and cross-linked drainage network (Krause et al., 2007).

The spatial patterns of land use within the Havel River catchment are very much controlled by the hydrological conditions. Due to wet conditions from autumn to spring, the central floodplain is characterised by extensive pasture and heathland whereas dry conditions and deep groundwater levels in the hillslope areas (moraines) means that land cover tends towards mixed and coniferous forests. Only the peripheral parts of the floodplain, which are at greater distance from the surface water and are characterised by intermediate groundwater depths, are used for intensive agriculture.

In the research area, meteorological variables from four climate stations, groundwater stages at observation wells, surface water levels at 14 gauges and soil moisture contents in vertical profiles at four stations were observed in order to gain process knowledge and to provide information for the parameterisation and characterisation of initial and boundary conditions for the model (Krause and Bronstert, 2007).

The research presented in this study focuses on the central part of the floodplain of the Lower and Central Havel River where the water balance is characterised by direct interactions between groundwater and surface water. Therefore, the so-called 'direct catchment' has been delineated by

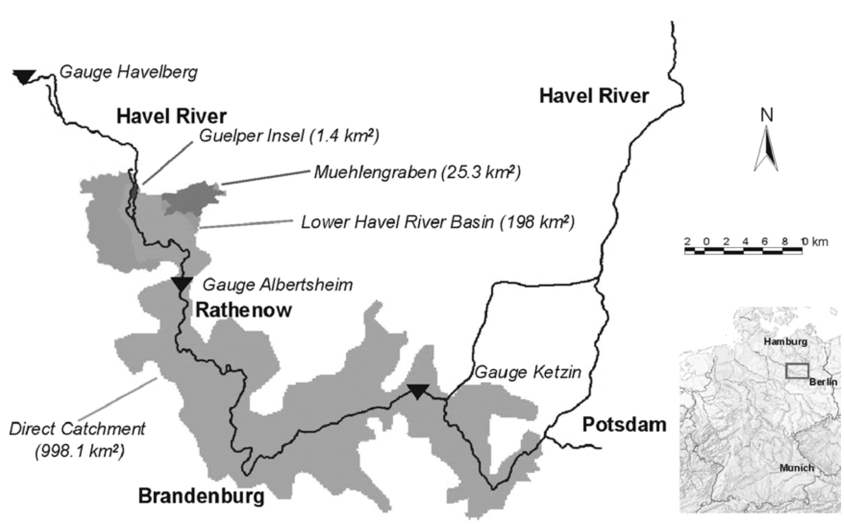

Figure 1 Location of the research area at the Lower and Central Havel River in Germany including the catchments ''Guelper Insel'', ''Muehlengraben'', ''Lower Havel'' and the direct catchment of the Lower and Central Havel river and locations of the main discharge gauges.

Table 1 Nested catchments at the Lower and Central Havel River: modelling purposes, spatial extent and space—time resolution for the model applications

Catchment	Model purpose	Simulation time	Time step	Spatial resolution (raster) (m)	Area (km^2)
Guelper Insel	Model calibration	4 month	1 h	25	1.43
Muehlengraben	Model calibration	4 month	1 h	25	25.38
Lower Havel	Model validation	1 yr (several yrs)	1 d	50	189.1
Direct Catchment	Water balance simulation	13 yr	1 d	250	998.1

the maximum spatial extent of the direct (i.e quick and tight) interactions between groundwater and surface waters. It has been assumed that the groundwater dynamic beyond this boundary is not directly connected to surface water stage fluctuation (Fig. 2; Krause and Bronstert, 2007). Hence, in the model the outer margins of the Direct Catchments are represented by no flow boundary conditions. An algorithm based on local simulation results in smaller subcatchments of the Havel River (Krause and Bronstert, 2007) was developed and applied in order to delineate the direct catchments boundaries (Krause and Bronstert, 2005). The investigated stream reach represents a 112 km long river section between the gauges ''Potsdam'' (Havel-km 194) and ''Garz'' (Havel-km 306).

Nested discharge observations

To investigate the pattern of discharge contributions from different parts of the Havel River catchment, discharge time series of three gauging stations in the upstream (Ketzin, Havel-km 213), central (Albersheim, Havel km 291), and downstream (Havelberg, Havel km 325) sections of the research area (Fig. 1) were compared for the period from 01.01.1990 to 31.12.1999. The accuracy of the ultra sonic based discharge measurements at these three gauges is assumed to be very high with an observation error of usually <5%.

The runoff q_{lat}, generated within the catchment area draining laterally into the river stretch bounded by two gauges can be calculated as the difference between downstream Q_{down} and upstream discharges Q_{up}.

$$q_{lat} = Q_{down} - Q_{up} \quad (1)$$

The discharge difference is the sum of both, the runoff contributions from tributaries and the direct exchange fluxes between the river and the groundwater within the floodplain assuming that there is no groundwater underflow that bypasses the gage.

The proportion of the discharge difference q_{prop} between downstream and upstream gauges on the downstream hydrograph represents the percentage fraction of runoff which is generated within the catchment limited by both gauges,

$$q_{prop} = (Q_{down} - Q_{up}) \times 10^{-2}/Q_{down} = q_{lat} \times 10^{-2}/Q_{down} \quad (2)$$

For assessing the spatially and temporally variable contributions from different parts of the catchment, the observed discharges between the upstream and downstream gauges (Ketzin and Havelberg), the upstream and the midstream gauges (Ketzin and Albertsheim), and the midstream and the downstream gauges (Albertsheim and Havelberg) are

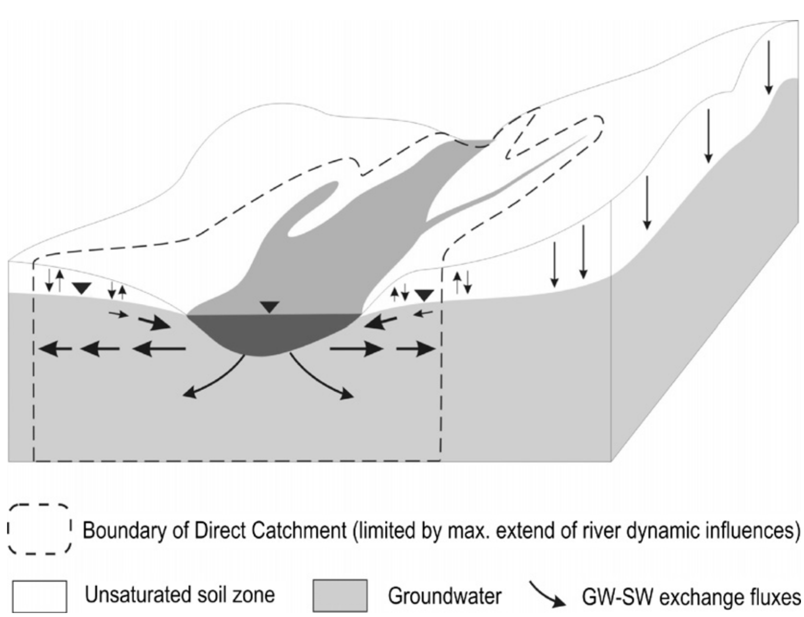

Figure 2 Boundary of the direct catchment, representing the area of the riparian floodplain where the water balance is controlled by 'quick and tight' interactions between the groundwater and the surface water.

compared (Section ''Nested observations of discharge dynamics'').

Process oriented modelling approach

For quantifying the groundwater—surface water interactions described above, a coupled soil-water and groundwater model was applied. The model simulates transient fluxes between the river and alluvial aquifer, which are evaluated in terms of the floodplain water balance and direction and magnitude of groundwater flow.

Underlying concepts

The IWAN model (Krause and Bronstert, 2005, 2007), which stands for ''Integrated Water Balance and Nutrient Dynamics Model'', considers the mainly vertical water balance processes within the unsaturated part of the floodplain and the coupled lateral flow processes of the groundwater. It takes into account the temporally and spatially variable exchange fluxes at the groundwater surface water interface. The model is based on the coupling of existing model routines and is composed of two main components (Fig. 3), which have been coupled in a two-way mode, i.e. feedback effects are taken into account in both directions:

1. Vertical soil water dynamics in the unsaturated zone is simulated by using routines from the deterministic, spatially distributed hydrological model WASIM-ETH-I (Schulla, 1997; Schulla and Jasper, 1999; Niehoff et al., 2002).
2. The flow in the saturated zone and its interactions with the channel systems is modelled by using the three-dimensional finite difference based numerical groundwater model MODFLOW (Harbaugh and Mc Donald, 1996a,b) and Processing MODFLOW (Chiang and Kinzelbach, 1993, 2001).

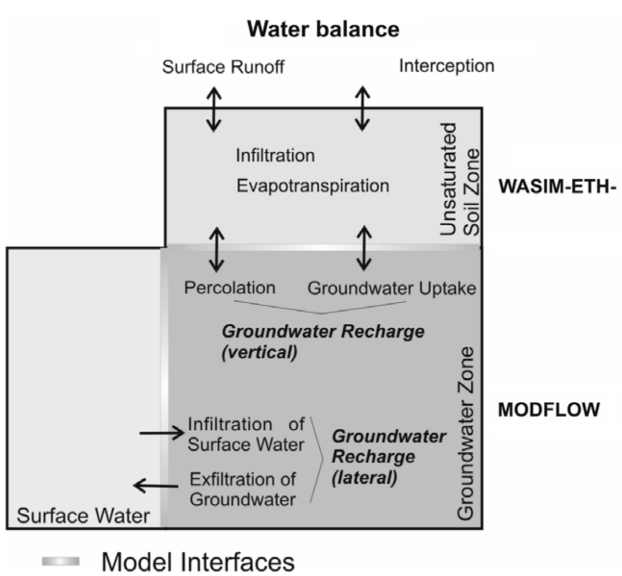

Figure 3 Concept of the coupled water balance and groundwater dynamic routines within the IWAN model: WASIM-ETH for calculation of the vertical soil water dynamics and percolation fluxes in the unsaturated zone and MODFLOW for approximation of the lateral groundwater flow for saturated conditions and for the interaction between groundwater and surface water.

Relevant process descriptions

The model approach enables the simulation of water balance for landscape types as described above, considering the direct influences of groundwater dynamics as well as of surface water interactions on the water balance of the whole lowland-floodplain system.

The model system does not dynamically simulate surface runoff on the floodplains or in the channel system. In accordance with experimental observations only vertical processes are considered within the unsaturated zone part of the model. The surface water stages are predefined as boundary conditions as given by the observed values.

The exchange between surface water and groundwater (Fig. 2) is approximated in the model-environment of Processing MODFLOW using the ''River Routine'' (Prudic, 1988; Rembe and Wenske, 1998; Fleckenstein et al., 2006; USGS, 2005). Hereby the exchange rate q (Eq. (3)) is calculated by a standard a leakage-approach. The leakage factor C_{RIV} (Eq. (4)) and the pressure head gradient Δh control the fluxes through the river—groundwater interaction, which is described as a pressure head boundary-condition in the groundwater module:

$$q = C_{RIV} \cdot \Delta h \tag{3}$$

$$C_{RIV} = K_{RIV} \cdot L \cdot \frac{W_{RIV}}{M_{RIV}} \tag{4}$$

where C_{RIV} = leakage factor (L^2T^{-1}); K_{RIV} = hydraulic permeability of riverbed (LT^{-1}); L = river length (L); W_{RIV} = effective river width (L); M_{RIV} = thickness of hyporheic zone (L).

As both equations are solved individually for each model time step at each model grid cell which is identified as a river cell this approach enables the consideration of the temporally and spatially variable extent of the interactions between the groundwater and the surface water.

The coupling of runoff generation and vertical soil water processes of the unsaturated zone modelled in WASIM-ETH-I and of the lateral flows and exchange processes with surface waters simulated in MODFLOW (Fig. 3) occurs by transmitting the outflows and inflows from the WASIM-ETH-I groundwater storage as groundwater recharge or uptake to MODFLOW and vice versa.

A more extended description of the model development and a detailed explanation of the coupling routines are given in Krause and Bronstert (2004, 2007).

Model setup

The boundary conditions at the river are determined by the pressure heads of the river cells. Therefore the observed river water levels from 14 surface water gauges along the Havel River are interpolated linearly.

For the determination of the upper boundary condition of the soil water balance (interaction with the atmosphere, i.e. evapotranspiration and rainfall) we used hydro-meteorological data from four climate stations. The parameterisation of vegetation, landuse and physical soil characteristics was tailored to apply a Penman-Monteith approach (Schulla, 1997). The application of the land-use data is comprehensively explained in Krause et al. (2007).

The spatial and temporal variability of the investigated landscape and the prevailing processes are approached by a non-stationary and spatially distributed model setup. For the analysis of water balance processes within the direct catchment model simulations were performed for a 13 yr period (1988—1999). To simplify model coupling, both model parts were run at a daily time step and with a spatial raster resolution of 250 m. However, for the calibration and validation of the model, the temporal and spatial resolutions were higher (Table 1).

Calibration and validation of the model

As the IWAN model does not dynamically simulate river discharge, and the observed surface water levels in the river are effected by river management measures (gates, weirs) discharge records were considered to be inappropriate for evaluating model efficiency.

Hence, calibration and validation of the model were carried out by comparing the simulated and measured groundwater stages at observation boreholes (Krause and Bronstert, 2004, 2007). This enables spatially distributed examinations of the model results, which is not the case if river discharge records are used as efficiency criteria.

For the evaluation of systematic over- or under estimation in the simulations, in addition to the Nash and Sutcliff Efficiency (NSE), the BIAS fraction of the mean square error (MSE) was also analysed (Krause and Bronstert, 2007). For MSE $\neq$ 0 the BIAS fraction is calculated by:

$$\mathrm{BIAS} = \frac{(\overline{O}_i - \overline{P}_i)^2}{\mathrm{MSE}} \tag{5}$$

where O = observed value, P = simulated (predicted) value.

The IWAN model system was calibrated for two smaller subcatchments (Fig. 1) the ''Guelper Insel'' (1.43 km^2) catchment and the ''Muehlengraben'' catchment (25.38 km^2) (Krause and Bronstert, 2005). During the calibration process, the leakage factor C_{RIV} of the hyporheic zone (controlling the fluxes between groundwater and surface, Eq. (4)) was used to minimise the difference between observed and simulated groundwater stages.

Fig. 4 shows the comparison between the observed and simulated groundwater stages for example observation wells in both subcatchments. The best correlation between observed and simulated groundwater stages could be obtained for K_{RIV}:M_{RIV} ratios of 1:1—10:1 (Krause and Bronstert, 2007), reaching NSE of up to 0.98.

The model was successfully validated within the 189.1 km^2 Lower Havel river basin. For the validation within this catchment, data for 22 observation boreholes were available. The validation was carried out for several hydrological years, covering a broad range of conditions from very dry to very wet years.

Table 2 represents the NSE and BIAS for the model validation from gauges within the central part of the floodplain (max. surface water distance = 2000 m) and for the peripheral regions at greater distances from the surface water.

Thus it was possible to show that there is no systematic model failure and that the range and dynamics of the observed groundwater levels could be satisfactorily predicted by the model for the central floodplain as well as for the more peripheral areas.

A model efficiency of NSE = 0.82 on average and an average BIAS below 0.2 were obtained (Krause and Bronstert, 2007).

A more comprehensive discussion of the parameterisation, model calibration, validation and application limits can be found in Krause and Bronstert (2007).

Table 2 Nash—Sutcliff Efficiency (NSE) and Bias for the validation period distinguishing between the floodplain part (<2000 m distance to the river) and the hillslope sections (>2000 m distance to river) of the Lower Havel river catchment (Figure 1)

	NSE (average)	BIAS (average)
Floodplain	0.83	0.13
Hillslope	0.75	0.32

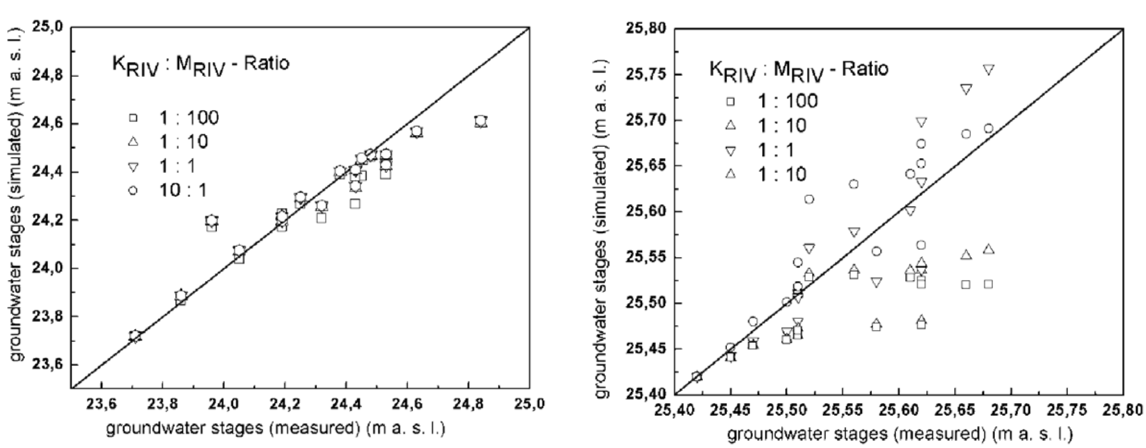

Figure 4 Comparison of observed and simulated groundwater stages during the calibration period for the ''Guelper Insel'' catchment (left) and the ''Muehlengraben'' catchment (right).

Results and discussion

Nested observations of discharge dynamics

The monthly discharge data of the Havel River measured at the Havelberg (most downstream) gauging station were averaged over a 10 yr time period (Fig. 5). The observed stream flow has a significant seasonal periodicity, characterised by higher discharges of 100–150 $m^3 s^{-1}$ from November until May and a low flow season with discharges of about 50 $m^3 s^{-1}$ during summer. However, the range and the upper and lower quartiles of the monthly data indicate a high inter annual variability in the data (Fig. 5).

The comparison of the nested observed discharges also indicates a substantial spatial variability of discharge contributions. The fraction of discharge generated within the research area on the total discharge of the Havel River (Fig. 6, top) shows a high temporal variability. The overall discharge proportion of the research area to the total discharge is 38%. However, for some periods the discharge fraction is higher than 50%. On the other hand this fraction occasionally becomes negative, indicating that the observed upstream discharge is higher than the observed downstream discharge. The Havel River loses water during these periods as the result of surface water exfiltration into the floodplain. The intensive temporal variability of observed discharges indicates a high heterogeneity of runoff generation processes within the research area.

Furthermore, comparing the discharge fractions generated within the upstream part (Fig. 6, centre) and the downstream part of he research area (Fig. 6, bottom) differences in their relative discharge contributions become obvious. Both sections have a relatively similar stream length and cover a similar catchment size. The overall discharge contribution of the upstream section between Ketzin and Albertsheim on the total discharge measured at the outlet in Havelberg is 22.88% (Fig. 6, centre), the contribution of the downstream part between Albertsheim and Havelberg is only 15.1%. The comparison of the spatial dynamics of discharge contributions on a seasonal basis detects even stronger heterogeneities as shown for the years 1994 and 1995. As the discharge observations are based on ultra sonic measurements the data are of a high accuracy (<5% average error) and the analysed differences of discharge contributions clearly exceed the data uncertainties.

Simulation of riparian water balance at the Lower and Central Havel River

The analyses of water balance and exchange fluxes within the Direct Catchments of the Lower and Central Havel River is based on the simulation of the entire direct catchments of the Lower and Central Havel River as well as on simulations of example subcatchments of the Lower Havel catchment (Fig. 1).

Simulation of exchange fluxes between floodplain and lowland river

Temporal variability of exchange fluxes. Fig. 7 shows the simulated exchange fluxes within the Lower Havel River catchment for the period 10/2001–10/2002. Three major phenomena can be observed for this period:

(i) Exchange fluxes between the floodplain's groundwater and the surface water can be observed in both directions during the simulation period. Effluent fluxes of groundwater are discharging into the stream as well as influent fluxes of surface water feeding into the groundwater.
(ii) For around 50% of the simulation period, exchange fluxes in opposite directions between groundwater and surface water coincide temporally. At the same time, one stream section of the river is losing water while in another section it is gaining water from the groundwater.
(iii) The balance between exfiltration and infiltration (i.e. the net exchange) depicted in Fig. 7 indicates whether the overall effect of exchange fluxes temporally characterises the river as temporally losing or gaining. During some periods the coincidence of contrary fluxes results in balanced conditions (as in August and September) when infiltration and exfiltration rates are equal.

Thus, the interactions between groundwater and surface water in the research area can be described as temporally

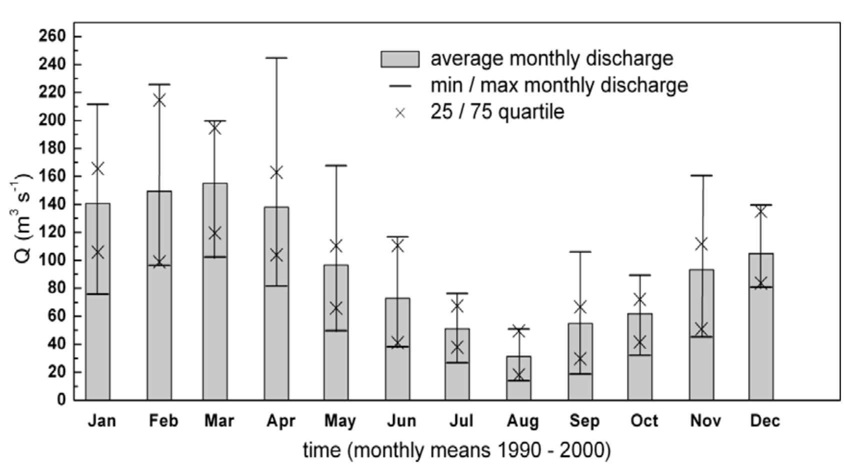

Figure 5 Mean annual dynamics of the observed discharges at the Havel River, averaged for the period from 1988 to 2000.

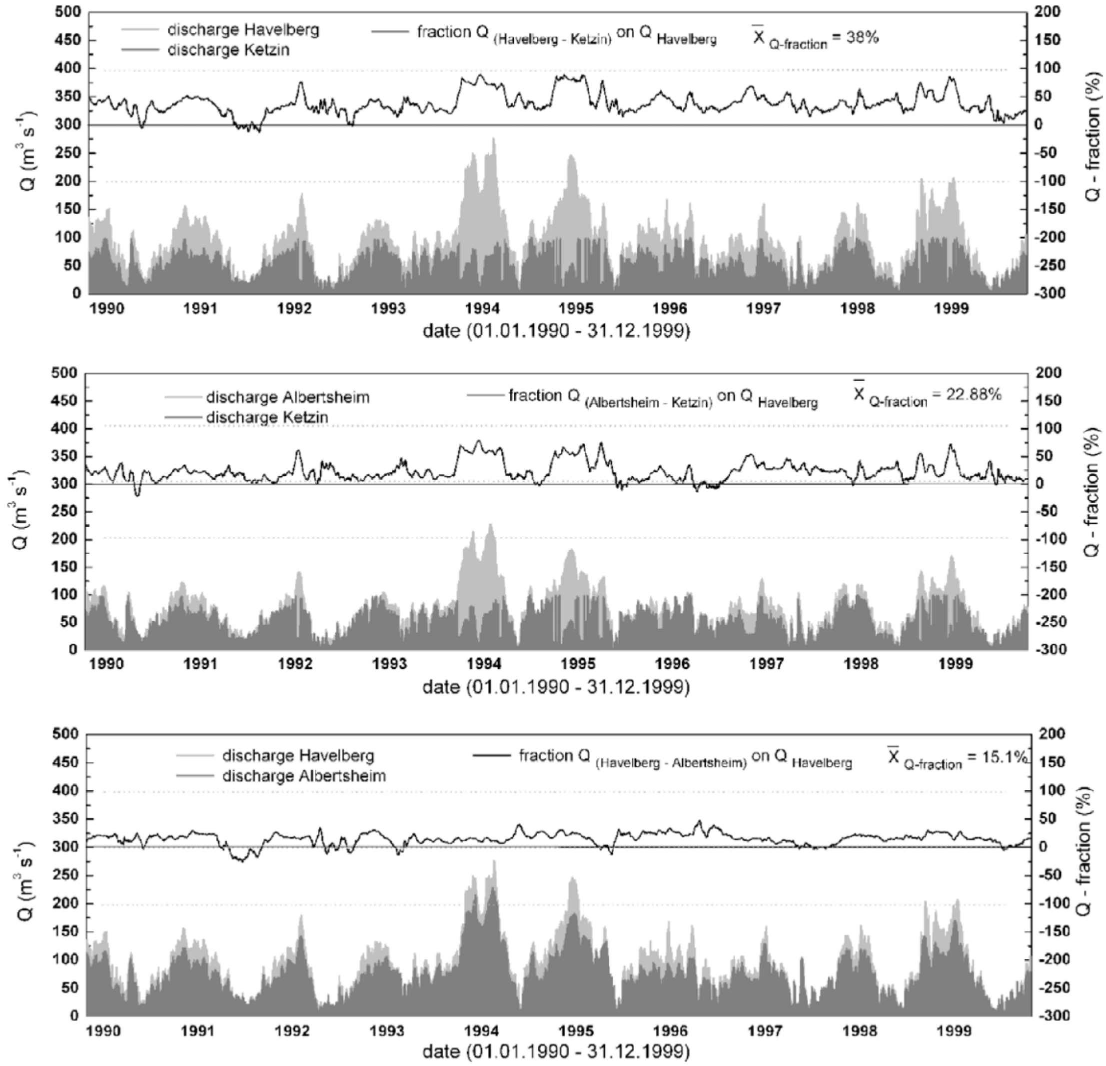

Figure 6 Comparison of observed discharges upstream, downstream and in the central part of the research area with respect to the proportion of runoff which is generated between the upstream and downstream gauges (top), between the upstream and central gauge (centre) and between the central and downstream gauge (bottom).

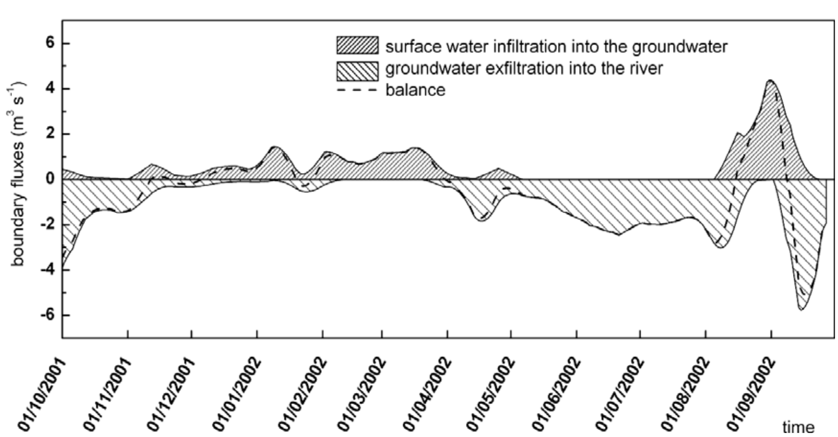

Figure 7 Simulated groundwater—surface water exchange fluxes in the ''Lower Havel'' catchment for the period 01.10.2001 — 30.09.2002 comparing groundwater exfiltration, surface water infiltration and the resulting net fluxes.

heterogeneous, variable in its intensities and flow directions. Due to unsteady exchange flow directions it is often not possible to clearly characterise the exchange fluxes as to be influent or effluent as it is described in Sophocleous (2002) or Woessner (2000). Furthermore, bank storage may have a short-term impact on the temporally variable groundwater—surface water exchange fluxes (Konrad, 2006; Laenen and Bencala, 2001; Fernald et al., 2001). For enabling an assessment of the overall impact of groundwater—surface water interactions for a particular point or stream reach for some limited applications the net exchange fluxes may be considered.

Spatial pattern of exchange fluxes. In addition to the intensive temporal variability of the exchange processes between groundwater and surface water, a substantial spatial heterogeneity of exchange fluxes at the groundwater—surface water interface could be observed.

Fig. 8 depicts for an example date the fluxes along the groundwater — surface water interface in a model section at the most easterly upstream part of the direct catchment. This stream section does not contain any manmade structures such as weirs.

For the simulation period, opposite flow directions can be detected in different parts of the subsection. The spatial pattern of flow directions allow assumptions about the general flow regime across each stream section for the particular date presented in Fig. 8 with gaining (infiltration only), losing (exfiltration only) and occasionally throughflow conditions with infiltration on the one side and exfiltration on the other (Woessner, 2000; Sophocleous, 2002).

As no disturbance due to water level regulating measures takes place at this particular part of the research area, we can assume that the exchange fluxes presented in Fig. 8 are only a result of the geo-morphological setting and hydraulic conditions e.g. heterogeneity in transmissivity and pressure head gradients. However, a substantial impact of the numerous weirs regulating the Havel River water levels could be observed for the entire research area (Fig. 1) (Krause et al., 2007). As a result, different flow regimes upstream and downstream of the weir (surface water infiltration upstream and groundwater exfiltration downstream the weir) can be induced.

Mean monthly exchange rates. For the analysis of the long term seasonal variations of exchange fluxes in Fig. 9 the simulated mean monthly exchange rates within the entire direct catchment of the Lower and Central Havel River were averaged over the 13 yr simulation period (1988—2000). The depicted fluxes represent the net exchange rates resulting from surface water infiltration and groundwater exfiltration.

On average the late spring and summer months (April—September) are characterised by a net groundwater discharge into the surface water (Fig. 9). The average groundwater contribution from April to September is 2 $m^3 s^{-1}$. From October until March the proportion of groundwater discharge to the river and surface water infiltration into the groundwater of the floodplain is nearly balanced with a slightly enhancement in surface water infiltration in November and December.

The range of exchange flows of individual years is relatively uniformly distributed for the summer months. During the remaining seasons, the average variability of individual years can differ significantly from the mean dynamics, for example surface water infiltration in January, which is balanced by overall groundwater exfiltration for the entire simulation period, can be up to 10 $m^3 s^{-1}$ for individual years.

Simulation of groundwater recharge in the floodplain

The net exchange rates presented above influence the groundwater recharge in the floodplain. The total groundwater recharge of the floodplain is a result of vertical processes (infiltration, percolation, evapotranspiration and root water uptake) as well as lateral or fluvial exchange fluxes between the groundwater and the surface water (Krause and Bronstert, 2004, 2007).

The model simulations for the 13 yr simulation period showed a specific seasonal variability of groundwater recharge and discharge periods (Fig. 10). The period from

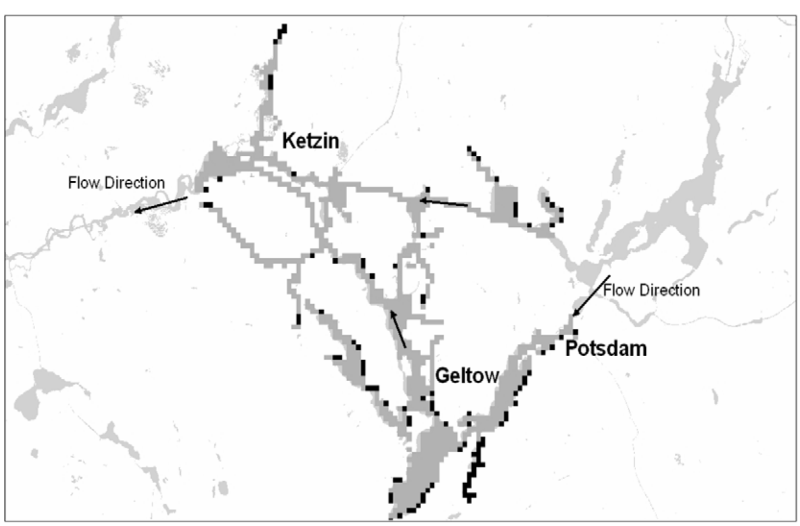

Figure 8 Spatial pattern of simulated groundwater—surface water exchange fluxes within the most upstream sub-section of the direct catchment of the Lower and Central Havel River.

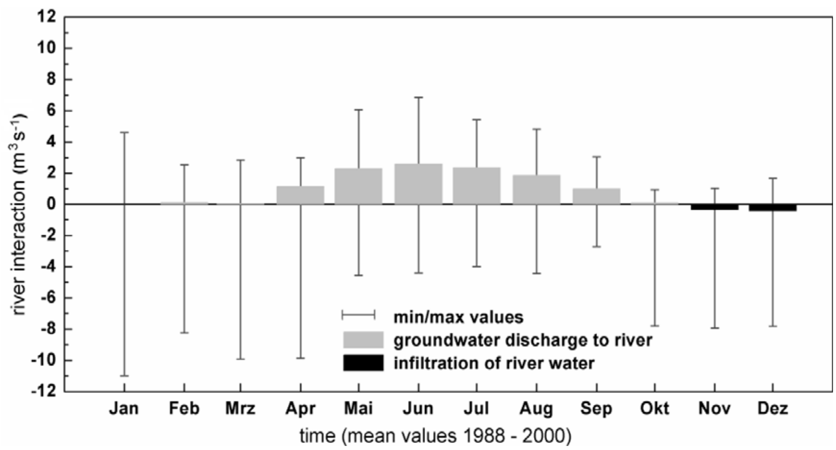

Figure 9 Mean monthly dynamics of the simulated net exchange fluxes between the groundwater of the riparian floodplain and the surface water within the direct catchment of the Lower and Central Havel River.

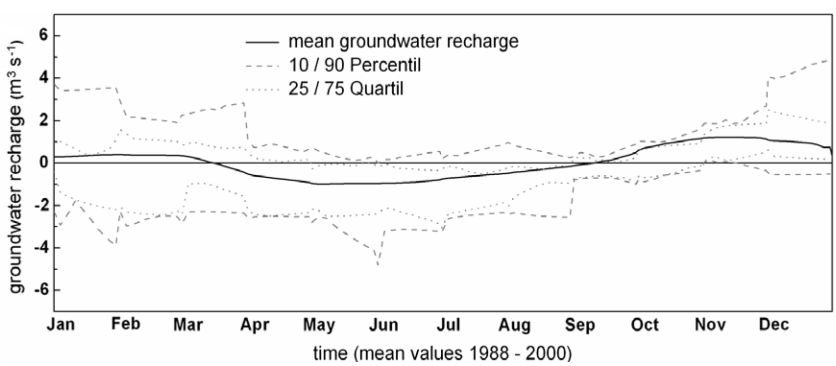

Figure 10 Simulated seasonality in groundwater recharge within the Direct Catchment of the Lower and Central Havel River as a result of lateral exchange fluxes with the surface water and vertical groundwater recharge generation by percolation or root water uptake.

September to April is characterised by average groundwater recharge of 0.5—1 $m^3 s^{-1}$. During the spring and summer (from April to August) mainly groundwater discharge occurs with rates of ca. 1 $m^3 s^{-1}$ (Fig. 10).

Considering the observed inter annual variability, characterised by the percentiles and quartiles shown in Fig. 10, different years may show different dynamics. Generally the highest inter annual variation of groundwater recharge could be observed during winter.

Impact of groundwater—surface water exchange fluxes on the total floodplain water balance and groundwater recharge

Taking into account the accordance of exchange fluxes along the groundwater—surface water interface and the temporal variability of floodplain groundwater recharge, it can be assumed that the floodplain water balance and the groundwater recharge are very much controlled by the interaction processes along the groundwater—surface water interface.

During the period of average surface water infiltration into the groundwater (mainly November and December), the net groundwater recharge is positive (Figs. 9, 10). Comparing the values of the average surface water infiltration rates (ca. 0.1—0.5 $m^3 s^{-1}$) and of the simultaneous groundwater recharge rates (0.5—1.0 $m^3 s^{-1}$) it appears that up to 50% of the groundwater recharge during this period results from lateral exchange flows, the rest of the recharge coming from atmospheric driven, vertical processes (rainfall—evapotranspiration).

During the summer months the average groundwater exfiltration rates of 2 $m^3 s^{-1}$ (Fig. 9) are higher than the simulated groundwater recharge (Fig. 10). This effect can be explained by the additional contribution to vertical groundwater recharge by percolating precipitation. However, it can also be observed that during different periods the groundwater losses (due to exfiltration into the surface water) can not be balanced by the vertical inflows, which causes a net groundwater discharge rate of ca. 1 $m^3 s^{-1}$ (Fig. 10).

Importance of riparian groundwater contributions for the river discharge

For evaluating the significance of groundwater contribution from the direct catchment of the Lower and Central Havel River for the total discharge of the entire Havel River, the simulated net exchange rates between the groundwater and the adjacent channel system of the Direct Catchment of the Lower and Central Havel (A_C = 998.1 km^2) are compared with the observed discharges of the whole Havel catchment (A_C = 24,000 km^2).

The simulated groundwater contributions are not higher than 10 m^3 s^{-1} at any time and can even be negative (surface water infiltration) whereas the maximum observed discharges at the catchment outlet are above 250 m^3 s^{-1} (Fig. 11). The average groundwater outflow of 0.81 m^3 s^{-1} represents only 1% of the average discharge (87.9 m^3 s^{-1}) at the river outlet. The groundwater contribution from the direct catchment of the Lower Havel River is generally not significant in comparison with the overall discharge and water budget of the Havel River. Comparing the proportion of the direct catchment area (4.2%) to the whole catchment area, it can be seen that the groundwater contribution from the direct catchment to the total discharge is a factor of four-times lower than the areal fraction.

For analysing the seasonal variation in the significance of groundwater—surface water exchange, the simulated mean monthly net exchange rates are compared to the observed mean monthly discharge (Fig. 12). The discharge differences between the river gauges upstream and downstream of the direct catchment are calculated. These differences represent the net runoff generated in the catchment area between both gauges and is the sum of runoff generated in the direct catchment and from further tributaries delivering runoff generated outside of the floodplain (but nevertheless within the catchment).

The average monthly values of observed discharges depicted in Fig. 12 is characterised by high runoff values from November to May (ca. 25 m^3 s^{-1}) and lower discharge differences from June to October (ca. 10 m^3 s^{-1}). Comparing the observed discharge differences with the exchange flows one can state that the fraction of groundwater in the total generated runoff is generally rather low for most of the year. However, during the low flow period in summer the groundwater fraction in the discharge is much more important, ca. 30% on average.

These findings highlight the seasonal variations of the direct groundwater contributions for the river discharge. Subsequently, the impact of exchange fluxes on the water quality and riparian ecology is likely to vary seasonally, both facts complement the concepts of riparian exchange processes and its ecological significance as described in Brunke and Gonser (1997), Sophocleous (2002), Hayashi and Rosenberry (2002), Hancock et al. (2005) or Woessner (2000).

Considering that the surface water levels within the research area are regulated by weirs and gates, the impact of such management measures on the pressure head gradients between groundwater and surface water needs to be taken into account.

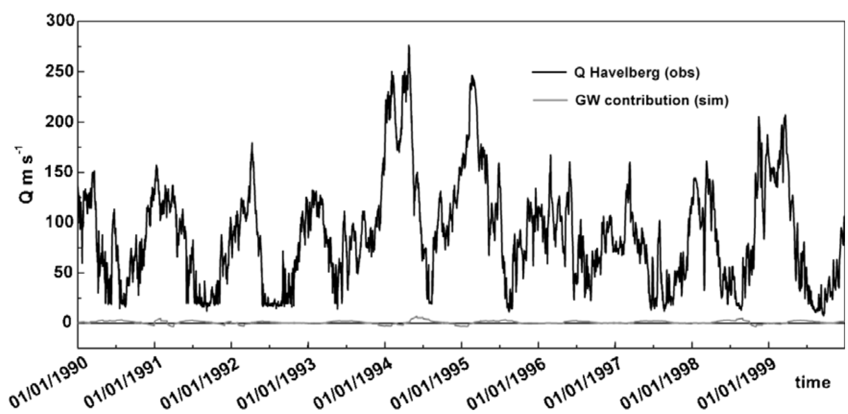

Figure 11 Comparison of discharge of the Havel River observed at gauge Havelberg (whole catchment area A_C = 24,000 km^2) and the simulated groundwater contribution from the direct catchment of the Lower and Central Havel (area A_C = 998.1 km^2) for the period 01.01.1990—31.12.1999.

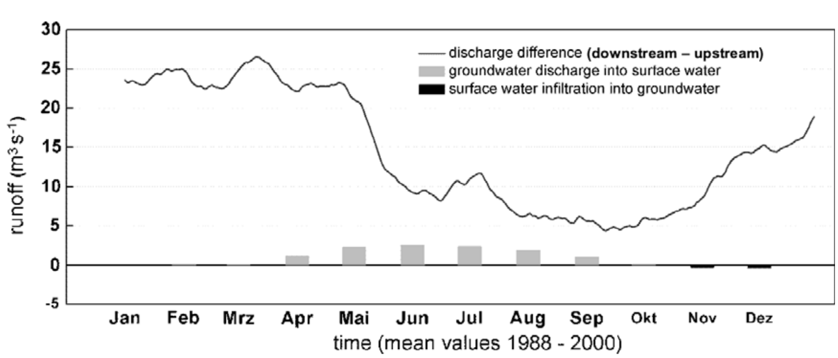

Figure 12 Comparison of the simulated groundwater exfiltration rates from the direct catchment of the Lower and Central Havel River and the observed discharge difference between the according upstream and downstream gauges.

As the main purpose of the surface water level regulations is to prevent high annual water level differences in order to avoid or at least mitigate high channel water levels and subsequent inundations in winter and otherwise to avoid low water levels in summer an attenuation of the annual water level amplitude is achieved. Hence, the pressure head gradients between groundwater and surface water can be assumed to be much higher and much more dynamic under non-regulated conditions which would cause even more intensive groundwater—surface water exchange fluxes and subsequently increase the impact on the riparian water balance and river discharge. Finally, as groundwater—surface water exchange processes are affected by the regulation of surface water levels an impact on related ecological functions of the floodplain and river can be assumed, which complements the list of anthropogenic influences presented in Brunke and Gonser (1997), Sophocleous (2002), Hayashi and Rosenberry (2002).

As mentioned earlier, the accuracy of the observed data is very high (average error <5%) and the estimation error of the model predictions is low (see efficiency of model validation results). Hence, the uncertainties associated with the comparison of observed and simulated data are sufficiently low to enable for valid conclusions. A detailed discussion of the limited application of the presented model is given in Krause and Bronstert (2007).

Conclusion

The experimental and model based analyses of the floodplain hydrology indicate temporally and spatially variable exchanges between the groundwater and the surface water in the research area. These fluxes are the most important control mechanisms for the water balance and groundwater dynamics of the floodplain and have a seasonally variable impact on the river discharge.

The observed discharges from a nested observation network prove a significant temporal variability in discharge within the research area, including a significant seasonal periodicity. Comparative analyses of discharge dynamics in different stream reaches of the Havel River show the spatial variability of runoff contributions from different subcatchments on the Havel River.

Simulations of the riparian water balance and groundwater fluxes with the coupled IWAN model system indicate a substantial temporal and spatial variability in the groundwater—surface water exchange fluxes in the research area. Heterogeneity in the spatial pattern of inflow and outflow to and from the groundwater was found and the simulation results indicate that the intensities and directions of these exchange fluxes frequently change. This is caused by an inversion of the hydraulic head gradients between river and riparian groundwater, which is either due to fluctuations of surface water levels or the higher water retention capacity of parts of the floodplain.

The traditional differentiation of gaining and losing stream sections does not apply for reaches with variable exchange directions, as it is not possible to clearly characterise a particular stream section as gaining or losing. Within the research area such classification can be identified only for temporary exchange flow conditions. However, the interactions between groundwater and surface water for a singular stream reach may be summarised by net-fluxes for annual means as losing or gaining type. In this sense, the investigated stream reach of the Havel River can be characterised as a gaining section of the river. On a sub-annual basis however, the same stream reach may change from losing conditions to gaining conditions and vice versa. Although the annual net balance of groundwater for the entire research area would characterise the Lower and Central Havel as a gaining river (groundwater exfiltration into the surface waters), during the winter especially, the surface water substantially feeds the riparian groundwater.

As the research area represents a typical example for lowland rivers in central Europe, we conclude that alternating exchange flow directions are likely to be characteristic for these riparian environments. Hence, future investigations may focus on the generation of a more dynamic system that also represents seasonal variability of flow directions.

The simulation of the floodplain water balance coupled with groundwater recharge dynamics proved the significance of the groundwater—surface water exchange fluxes for the total groundwater recharge of that area. Actually, the vertical groundwater recharge (percolation/uptake into/from the unsaturated soil from/into the aquifer) is — at least partly — counterbalanced by lateral exchange fluxes.

The comparison of simulated exchange fluxes and the observed discharges within the Havel River indicated that the proportion of groundwater exfiltration is low with a mean annual contribution of 1%. Within the research area, which represents 4.2% of the entire Havel catchment area, the impact of groundwater—surface water interactions on the annual discharge of the Havel River is only marginal. However, during the typical low flow conditions in summer, contributions from the riparian groundwater represent up to 10% of the total river discharge or 30% of the runoff which is generated within the entire catchment of the Lower and Central Havel River.

Considering the special ecological significance of low flow seasons for the conditions both in the river and in floodplains the high impact of groundwater—surface water exchange fluxes during summer is evident. During periods of extreme low flow conditions, the fluxes are crucial in determining the hydro-chemical conditions and resulting ecological stress during a time which coincides with the main vegetation growth period or algal blooms.

Taking into account the specific ecological sensitivity to summer low flow seasons, the singular use of the gaining/losing concept may not be appropriate to describe the role of groundwater—surface water interaction in the research area.

The results of this study prove that for eco-hydrological assessments in lowland catchments, the temporal and spatial dynamics of groundwater—surface water interactions need to be considered. It is not appropriate to evaluate the impact of exchange fluxes by annual net balances alone, but rather to take into account the impact these interactions may have during critical periods such as droughts or floods.

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